Project Summary Report FY2005
International Nuclear Energy Research Initiative

Development of Advanced Instrumentation and Control for an Integrated Primary System Reactor

U.S. Participants:

Oak Ridge National Laboratory
Westinghouse Electric Company LLC.

Brazilian Participants

Instituto de Pesquisas Energéticas e Nuclearares

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1. Executive Summary

This project is a collaborative effort between the U.S. and Brazil to develop the specialized instrumentation and controls technologies required for Integral Primary System Reactors (IPSRs). Oak Ridge National Laboratory and Westinghouse Electric Company are performing the U.S. portion of the project. The Brazilian team represents the Comissao Nacional de Energia Nuclear through its Instituto de Pesquisas Energéticas e Nuclearares. The project was initiated between February and June of 2005, consequently this report summarizes 2-3 quarters of effort. The report first presents an overview of the overall project description and rationale. Next the project tasks, responsibilities, and schedule are presented. Then each individual task that has been worked on during this initial reporting period is reported on sequentially.

Task 1, which was largely performed by Westinghouse, was to identify the instrumentation differences between IPSRs and more traditional external loop Light Water Reactors (LWRs). The starting point for this study was to review and synthesize general characteristics of integral reactors, but then to focus on a specific design. Due to their detailed knowledge of the system and its relative maturity, Westinghouse staff focused on the International Reactor Innovative and Secure (IRIS). The task has now been completed and technical report issued.

Task 2 focuses on developing instrumentation to resolve an already identified ISPR challenge—namely to provide an accurate, reliable, in-vessel coolant level measurement system. Two candidate systems are currently under development. ORNL is pursuing an ultrasonic, torsional waveguide-based level measurement technique, while IPEN is developing a cooled lance type liquid level probe featuring advanced signal processing to yield a continuous liquid-level measurement. ORNL has thus far developed an initial finite element based model for the ultrasonic waveguide and has performed initial experimental benchmarking of the model predictions. ORNL is currently developing a more advanced experimental prototype suitable for deployment in more rigorous environments as well as beginning to develop the customized signal processing required to interpret the measured signals. IPEN is currently nearing completion of their experimental test facilities to enable demonstration of their probe concept in a representative environment as well as to begin to acquire measured data to train their signal processing system.

During FY2005, Task 3 has focused on adapting a self-organized-map transient identification technology to IPSRs. IPEN has led this effort and is collaborating with Westinghouse in applying the existing Westinghouse thermal models for the IRIS reactor to the transient identification system. This year's effort has been primarily directed towards methodology refinement and stability assurance.

Tasks 4 and 5 are presently initiating with Westinghouse beginning to develop an overall control strategy for a nuclear power park containing several reactor units that transition between different production objectives depending on the present market opportunities and ORNL investigating demonstration of this strategy onto a test bed.

2. Project Overview

IPSRs have distinctive Instrumentation and Controls (I&C) configurations and requirements as compared to more traditional external loop LWRs. The common thread binding the project tasks together is development of specialized IPSR I&C technologies not directly transferable from external loop LWRs. At the initiation of this project, no systematic assessment of the I&C requirements for IPSRs was available to provide inter-comparison with known technologies from external loop LWRs. Performing a detailed review of the instrumentation requirements for an IPSR thus became a leading task for this project.

An already identified instrumentation challenge for IPSRs is accurate in-vessel water level measurement. The irregular path imposed by the shape of the pressurizer bottom plate, riser, control rod drive mechanisms, and other structural components make the use of conventional level measurements almost impossible. A major project task is therefore to develop an in-vessel level measurement system deployable in an integral configuration. Two candidate systems are currently under development: (1) an ultrasonic, torsional waveguide-based level measurement technique and (2) application of advanced signal processing algorithms to a cooled-fluid-based lance type probe.

An additional objective of the current project is to assess areas in plant operation and control where IPSR features and operating modes require innovative approaches. The IPSR medium size and modularity provides economic incentives for deployment of multiple reactor modules in a single nuclear park. Co-generation (production of desalted water, district heat industrial steam, hydrogen, etc.) is an attractive option for modular reactors that are sited in areas with sufficient electrical generation capacity to supply base load power. In order to fully use the energy available from all reactors in a nuclear park, the balance of plant needs to be reconfigurable to allow time varying co-generation with changes in the electrical load. In order to optimize multi-modular and/or reconfigurable operation, a hierarchical supervisory control system needs to be developed to overlay the individual unit control system. The primary importance of the hierarchical control development task is thus to maximize the utilization efficiency of the power-park resources while minimizing staffing requirements.

The final technical area of the project is development of the guidelines for interaction of the operator with the plant control and protection systems. A feature of advanced IPSRs (and IRIS in particular) is that, unlike the current external loop LWRs, they are designed to be capable of responding to almost any operational or accident condition without requiring operator action. IPSRs are typically characterized by long transient evolution times, due to the large thermal inertia of the primary system. Due to the advantageous thermal characteristics of IPSRs as compared to external loop LWRs, the operator interaction with the control/protection systems needs to be redesigned. Further, emergency procedure guidelines and control room architectures, taking into account the possibility of controlling multiple modules from a single control room, and human/machine interfaces reflecting the distinctive characteristics of IPSRs will be evaluated as this project progresses. Part of the redesign of the operator to plant interaction being pursued is to develop the ability to rapidly identify and classify transient events. The transient identification and classification system under development is based on self-organized maps, a special class of artificial neural networks. The system, when fully developed, will operate on-line in parallel with the reactor controls and is intended to serve as an advanced tool to support operator actions and decision-making.

3. Tasks, Responsibilities, Schedule, and Milestones

The project consists of five major tasks:

1. Identification of the instrumentation needs for IPSRs, and specifically where additional development is required (Westinghouse)
2. Development and demonstration of high reliability, high accuracy water level measurement technologies directly applicable to in-vessel nuclear power plant applications (ORNL & IPEN)
3. Development of a reactor transient identification and classification system supporting safe and reliable reactor operation (Westinghouse & IPEN)
4. Creation of a hierarchical, supervisory control scheme for the IRIS reactor supporting both multimodular deployment and balance-of-plant reconfiguration, (Westinghouse & ORNL) and
5. Characterization of the operator interaction with the control and protection systems with emphasis on the design considerations of common control rooms for multi reactor plants built using sequential construction (Westinghouse & IPEN).

Task 1 was the major focus for Westinghouse's effort during FY2005. The task was successfully completed with the issuance of the topical report "Instrumentation Needs For Integral Primary System Reactors (IPSRs)" at the end of September 2005.

Task 2 is subdivided into two alternative approaches. ORNL is implementing an ultrasonic torsional waveguide based level measurement while IPEN is implementing a cooled lance base approach. Task 2 was the major focus for ORNL's technical effort during FY2005. ORNL achieved two milestones under task 2 during FY2005. 1) By June 30th, ORNL had completed an initial finite element model of the acoustic wave guide level sensor. 2) By August 30th, ORNL had successfully performed a benchmark measurement confirming the prediction of the finite element model. Task 2 was also a major focus for IPEN's efforts during FY2005. During this period IPEN performed an initial literature review confirming the state-of-the-art and performance of thermal probe based level measurements and completed ~90% of their probe test facility design and implementation.

Task 3 was a significant area of technical effort for IPEN, with participation of Westinghouse. During the FY2005, Westinghouse has transferred the initial RELAP model of IRIS (developed by Westinghouse and the University of Zagreb) to IPEN. The model will be further reviewed and revised during the FY2006. During this year IPEN staff have analyzed the RELAP model for IRIS and subdivided its transient behavior into a two dimensional self organized map (SOM) structure and began sensitivity analysis of variations in the mapping technique.

Tasks 4 & 5 Have not yet begun

4. R&D Status and Accomplishments By Task

4.1. IPSR Instrumentation Needs Review

While most of the signals required for control of IPSRs are typical of other loop-type Pressurized Water Reactors (PWRs), the integrated configuration poses some new challenges in the design or deployment of the sensors/instrumentation, and in some cases requires completely new approaches. In response to this consideration, the overall objective of Task 1 was to establish the instrumentation needs for integral reactors, provide review of the existing solutions where available, and identify research and development needs to be addressed to enable successful deployment of IPSRs.

The starting point for this study was to review and synthesize general characteristics of integral reactors, but then to focus on a specific design. Due to the maturity of its design, and availability of design information to Westinghouse, IRIS (International Reactor Innovative and Secure) was selected for this purpose.

The performed work was presented in detail in the report STD-AR-05-01(rev.1)[1] that is organized as follows:

Section 1 is a report overview.

Section 2 provides background information on several representative IPSRs, including IRIS. A review of the IRIS safety features and its protection and control systems is used as a mechanism to ensure that all critical safety-related instrumentation needs are addressed in this study.[2] Additionally, IRIS systems are compared against those of current advanced PWRs. The scope of this study is then limited to those systems where differences exist, since otherwise the current technology already provides an acceptable solution.

Section 3 provides a detailed discussion on instrumentation needs for the representative IPSR (IRIS), with detailed qualitative and quantitative requirements summarized in the exhaustive table included as Appendix A. Section 3 also provides an evaluation of the current technology and instrumentation used for measurement of required parameters in current PWRs.

Section 4 examines those instrumentation/measurement needs where differences between IRIS and present PWRs exist and the current PWR implementation cannot be directly employed, and identifies two sub-categories. In the first group, resolution can be readily identified, and is essentially an engineering solution (for example, modification of an existing approach, adaptation of existing instrument etc.). The second group presents true technological challenges as it may require new technology development. In these cases, high-level functional requirements have been identified together with relevant technical considerations to guide future development activities.

Thus, the overall approach that was used to systematically assess instrumentation needs may be summarized as follows:

- As a starting point: review and synthesize general characteristics of integral reactors
    - Collect background information on several representative IPSRs[3]
    - Focus on a specific design – IRIS selected due to the maturity of its design and availability of design information. IRIS integrated layout is shown in Figure 1.
- Review of the IRIS safety features and its protection and control systems. Use it as a mechanism to ensure that all critical safety-related instrumentation needs are addressed in this study
- Additionally, IRIS systems are compared against those of current advanced LWRs (e.g., AP600/AP1000)
- The scope is then limited to those systems where differences exist, since otherwise the current technology already provides an acceptable solution
- Instrumentation needs are examined and discussed for the representative IPSR (IRIS), with detailed qualitative and quantitative requirements summarized in the exhaustive table included as Appendix
- The current technology and instrumentation used for measurement of required parameters in current PWRs is evaluated for the compatibility with the IPSR needs
- Instrumentation/measurement needs are examined where differences between IRIS and present PWRs exist and the current PWR implementation cannot be directly employed; and classified into two sub-categories:
    - Resolution can be readily identified, and is essentially an engineering solution (for example, modification of an existing approach, adaptation of existing instrument etc.)
    - True technological challenges as it may require new technology development. In these cases, high-level functional requirements have been identified together with relevant technical considerations to guide future development activities.

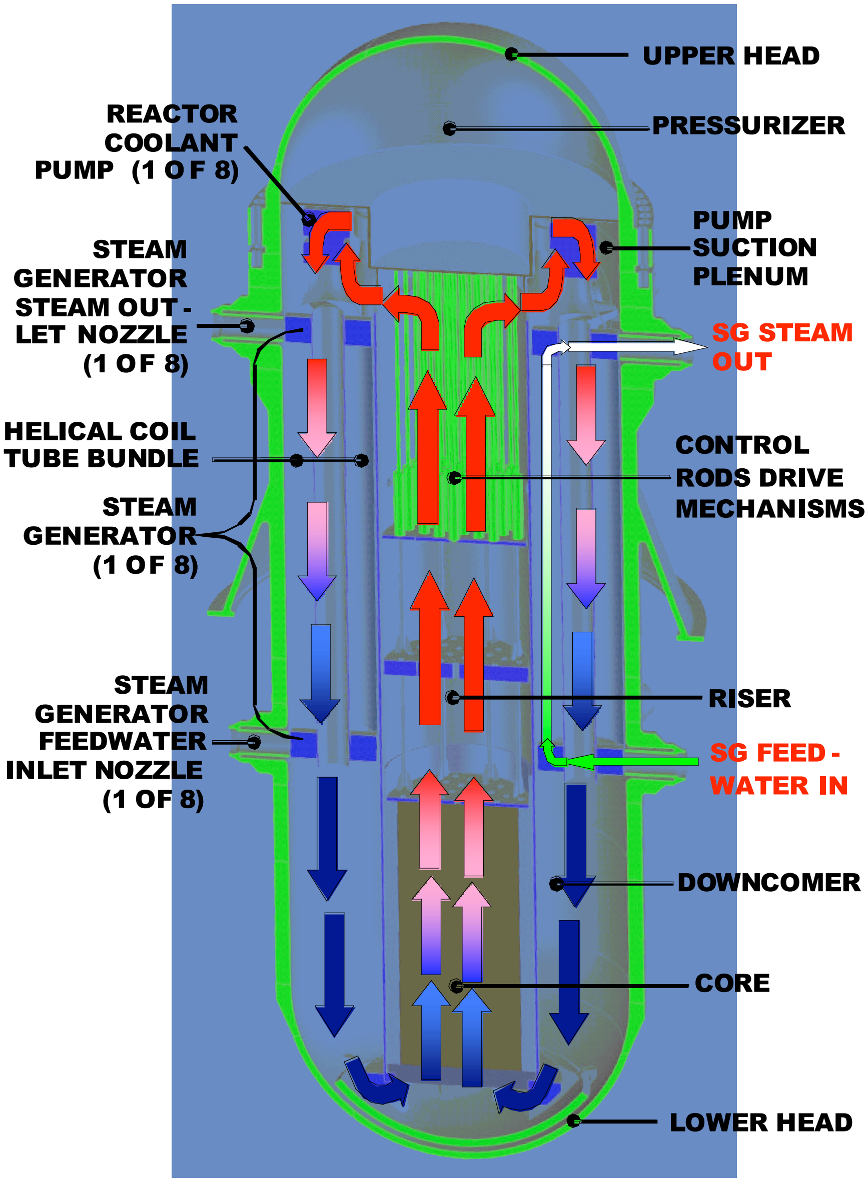

Figure 1. IRIS integral layout

Systematic assessment of all instrumentation needs is achieved by considering all identified instrumentation needs of the IRIS Control System (PLS) and Protection System (PMS).

The Control System (PLS) controls the plant operation through the following actuators:

- the control rods position,
- the feedwater flow to the steam generators,
- the steam dump system,
- the pressurizer pressure control system,

- the pressurizer level control system.

Whereas, the Protection System (PMS) has twofold function:

- Monitors the plant for abnormal conditions while alerting the operator to take appropriate corrective action if required;
- Provides automatic reactor trip (i.e. shutdown) and safety system actuation whenever plant conditions, as monitored by nuclear and process instrumentation, reach the plant safety limits.

A functional schematic of the Protection System is shown in Figure 2.

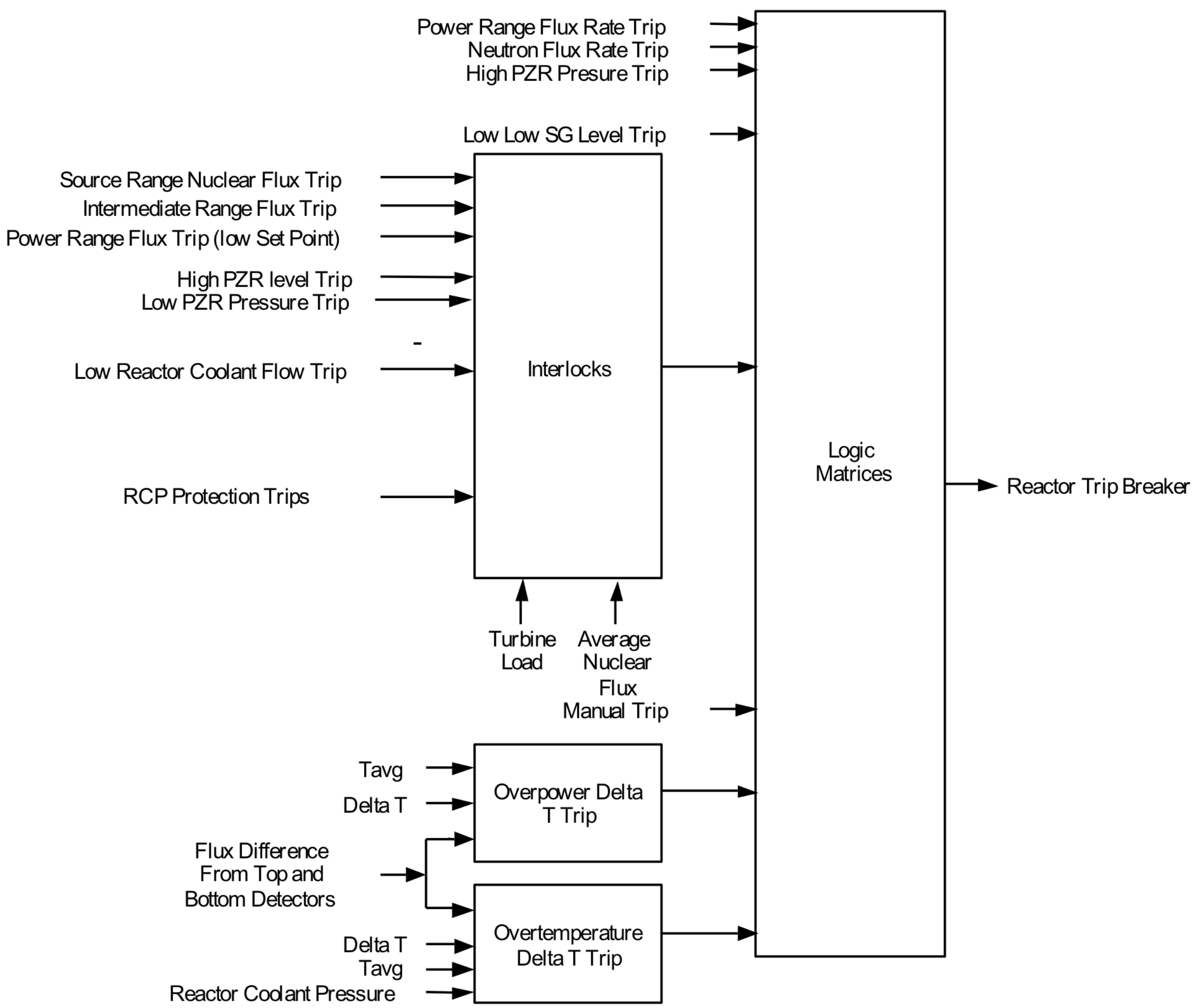

Figure 2. Protection System – Schematic

Instrumentation/measurement needs were considered (surveyed) for all relevant plant operating conditions (Table 1), and systems (Table 2).

Table 1. Plant operating conditions

MODES	TITLE	REACTIVITY CONDITION (Keff)	% RATED THERMAL POWER	AVERAGE REACTOR COOLANT TEMPERATURE
1	Power Operation	>= 0.99	> 5 %	NA
2	Startup	>= 0.99	<= 5 %	NA
3	Hot Standby	< 0.99	NA	> 215°C (420°F)
4	Safe Shutdown	< 0.99	NA	215°C (420°F) ≥ T_{avg} >93°C(200°F)
5	Cold Shutdown	< 0.99	NA	≤ 93°C (200°F)
6	Refueling	NA	NA	NA

Table 2. Systems considered

Systems addressed in the survey	
System Acronym	*Description*
RCS	Reactor Coolant System
ICS – RPS	Instrumentation & Control System – Reactor Protection System
ICS – PLS	Instrumentation & Control System – Plant Control System
ICS – DAS	Instrumentation & Control System – Diverse Actuation System
ICS – SMS	Instrumentation & Control System – Special Monitoring System
NFS – SGS	Nuclear Fluid System – Steam Generators System
NFS – EHRS	Nuclear Fluid System – Emergency Heat Removal System
NFS – ADS	Nuclear Fluid System – Automatic Depressurization System
NFS – EBS	Nuclear Fluid System – Emergency Boration System
NFS – LGMS	Nuclear Fluid System – Long term Gravity Make-up System
NFS – CPSS	Nuclear Fluid System – Containment Pressure Suppression System
NFS – PCCS	Nuclear Fluid System – Passive Containment Cooling System
NFS – CS	Nuclear Fluid System – Containment System

Detailed results of this survey are summarized in an exhaustive table, provided in Appending A of the Report STD-AR-05-01(rev1). A sample of the table is shown in Table 3.

Table 3. Instrumentation needs of IPSRs – sample table format

System	Process Parameter	Plant Condition	Function	Requirement	1E? Y/N	Protection? Y/N
Core	Nuclear power (total)	Refueling				N
		Shutdown	Provide continuous monitoring	Sufficient magnitude to determine signal is non zero within 10 seconds Reproducibility within one octave	N	N
			Uncontrolled reactivity addition protection	Reproducibility within one octave Time response<30 seconds Same for 5 min following SSLB or SSE	Y	Y
			Recording	Reproducibility to 0.1 decade		N
		Startup	Uncontrolled reactivity addition protection	Reproducibility within one octave Time response<10 seconds Same for 5 min following SSLB or SSE	Y	Y
			High flux protection	Accuracy $\leq$ 1 decade Reproducibility within 0.1 decade Time response < 10 s	Y	Y
			Allow operator to monitor startup	Startup rate signal Accuracy $\leq$0.1 dpm Noise<0.15 dpm Time response$\leq$30 s at low end Time response$\leq$1 s at high end		N
			Recording	Reproducibility to 0.1 decade		N
		Power Operation	High-power protection	Accuracy $\leq$ 7% Reproducibility within 1% Time response < 0.2 s Noise <0.5% Same for 5 min following SSLB or SSE	Y	Y
			(etc.)			

The survey concluded that in certain areas there does not seem to be a pressing need for new developments, i.e., the instrumentation used in loop LWRs may be used or easily adapted to IPSRs. However, the survey also identified areas where the need for development of new and/or advanced instruments exists. These areas specifically include:

1. Nuclear Instrumentation System (NIS). The thick downcomer typical of IPSRs, while beneficial for reducing reactor vessel embrittlement, also makes ex-core/ex-vessel neutron flux measurements more difficult. Ex-vessel measurement techniques typical for loop PWR are not feasible in IPSR, but instead ex-core/in-

vessel measurements are foreseen, indicating required development of a new NIS system.

2. Primary flow measurement. This measurement becomes more complex in integral configuration, as compared to a loop system with well-defined flow.

3. Reactor Coolant System temperatures. Similar considerations due to integral configuration.

4. Primary water inventory. This is being addressed within the complementary activities of ORNL and CNEN within the same I-NERI program.

5. Steam Generator water inventory. Due to placement of steam generators within the reactor vessel, IPSRs employ once-through steam generators, making their inventory determination more complex.

6. Steam Generator stability measurements. Also related to their internal placement.

The identified IPSR instrumentation needs will enable focused R&D to develop instrumentation required to enable ultimately successful (safe, and reliable), IPSR deployment.

Further details are provided in the report STD-AR-05-01.

4.2. *In-Vessel Level Measurement*

Following the Three Mile Island (TMI) accident, the U.S. NRC recommended the installation of instrumentation to "provide unambiguous, easy-to-interpret indications of inadequate core cooling."[4] The NRC's advisory committee on reactor safeguards amplified the recommendation stating:[5]

> *The Committee believes that it would be prudent to consider expeditiously the provision of instrumentation that will provide an unambiguous indication of the level of the fluid in the reactor vessel…*

Further, level measurement instrumentation needs to provide a dynamic mapping of the fluid density within the vessel as instrumentation providing only a single stationary liquid level reading of "full" during normal operation would likely be disregarded during an excursion.

4.2.1. Ultrasonic Torsional Waveguide Based Level Measurement

4.2.1.1 Task Overview

The objective of this task is to develop a torsional ultrasonic wave based in-vessel level measurement system deployable in an integral primary system reactor. The central idea underlying this type of sensor is that the density of the fluid in which a waveguide is submerged will affect the propagation velocity of a torsional wave along the waveguide. The FY2005 effort has had two main emphases: building an experimental apparatus to demonstrate the phenomena and creating a computational model for the measurement.

4.2.1.2 Background

The application of torsional wave propagation delay along a non-circular waveguide to fluid level measurement is not new. Lynnworth received a patent[6] for the idea in 1980 and Bau et al received a follow-on patent[7] in 1990 incorporating the concept of shaping the waveguide to maximize the signal strength. Also, following the TMI-2 accident, the NRC sponsored development of ultrasonic torsional guided wave, in vessel level measurement technology at ORNL during the early 1980s.[8,9,10,11]

Ultrasonic guided wave technology, however, was not selected as the preferred method for in-vessel level measurement in the early 1980s. Two primary technological challenges underlie ultrasonic guided wave technology not achieving commercial LWR deployment in the 1980s. First, passing a torsional ultrasonic wave across a massive, rigid pressure boundary such as a reactor vessel is challenging as the torsional wave energy couples strongly to the vessel. In order to overcome this difficulty, the new sensing system currently under development will be contained entirely within the reactor vessel. Only electrical signals need to pass through the pressure boundary. This approach is consistent with the location within the pressure boundary of several IRIS critical components, e.g., the control rod drive mechanisms and the reactor coolant pumps motors. The second previous technological difficulty was in interpreting the signals received from a complex multi-zoned waveguide to obtain a distributed fluid density map. The echo signal returned from the pulsed ultrasonic signal has information impressed upon it from every mechanical feature of the probe from weld joints to fiducial notches. Correctly interpreting this signal was computationally demanding for early 1980s digital signal processing (DSP) speeds, since signals have frequency content up to ~1MHz. The required computational power is now readily available.

Other organizations continued to pursue ultrasonic guided wave level measurement in static tanks in the 1980s and 1990s. However, commercial interest has now been restricted to providing density corrections to mass flowmeters due to difficulties with air bubble formation on and attachment to the surface of the waveguide in static situations, while in flowing media induced bubbles are swept away from the probe. The attached air bubble layer alters the local density around the probe preventing the sensor from functioning. LWR coolant is de-aerated to prevent free oxygen from attacking metal surfaces. Hence air bubble attachment will not be a problem in IPSRs. LWR coolants, however, do contain dissolved hydrogen. As the hydrogen content of the coolant is not near saturation, it is not anticipated that the ultrasonic probe will induce bubble formation. However, if bubbles are formed, coolant flow across the ultrasonic probe will prevent bubbles from adhering to the probe surface any time the coolant pumps are operating. Finally, even under stagnant conditions, hydrogen bubbles tend not to attach to hydrophilic surfaces[12] such as titanium dioxide[13], which is a leading probe material candidate.

4.2.1.3 Introduction

The principles underlying stress acoustic wave generation and propagation are well known. The concept that the surrounding medium will influence the propagation velocity of a torsional wave in a fluid immersed, non-circular, solid waveguide is apparent. Initial modeling of the phenomena and their application to fluid-density profile measurement was performed in 1977.[14] Conceptually, the speed of any torsional elastic wave propagating down a waveguide is proportional to the square root of the stiffness of the rod divided by the sum of the waveguide and the surrounding fluid inertia. A larger fluid inertia, therefore, results in a lower torsional wave propagation velocity. The fluid's apparent inertia is a combination of its density and viscosity. In the case of a water-like fluid, for realistic probe dimensions and ultrasonic wave frequencies, Kim and Bau have shown that the fluid viscosity can be neglected[15] resulting in a wave propagation delay inversely proportional to the fluid density. The other terms in the torsional wave propagation equation relate to the stiffness and inertia of the waveguide. Waveguide inertia is a constant while stiffness changes with temperature. The waveguide temperature, however, affects the length of the waveguide. Launching an extensional wave down the waveguide and measuring the return time enables measurement of the average waveguide temperature. A distributed temperature picture along the waveguide can be obtained by incorporating a series of fiducial notches along the waveguide. This enables direct compensation for temperature effects on the fluid density measurement. While this is not required under normal operating conditions for an IPSR when the primary coolant is in saturation and thus at constant temperature, temperature compensation would become important if the coolant becomes superheated during accident conditions or during startup. Fortunately, ultrasonic probe extensional wave thermometry has been repeatedly demonstrated for measurements in-core[16] as a departure from nucleate boiling diagnostic, and indeed in molten corium temperature measurements.

Magnetostriction is a property of any ferromagnetic material and arises as the magnetic domains within the material are aligned by an external magnetic field. The domain alignment results in a stress wave (extension) in the material parallel and anti-parallel to the direction of the applied magnetic field. An extensional wave can thus be produced in a ferromagnetic rod by wrapping a solenoid coil around it and subsequently applying current to the coil. Applying AC current to the coil produces synchronous extension and relaxation of the rod. This in turn results in strain waves that propagate down the rod. The change in dimension of a ferromagnetic material when exposed to an external magnetic field is known as the Joule effect. In Figure 3, a current pulse introduced into a coil surrounding a ferromagnetic rod creates a magnetic flux transient in the rod that causes a change in its length by the Joule effect.[17] This sudden change in length produces an acoustic stress pulse that at the speed of sound propagates within the material as an extensional wave. Conversely, a returning extensional stress pulse passing under the coil produces a local dimensional change, which then generates a change in flux that links back to the coil. This change in flux produces a voltage across the coil in accordance with Faraday's law (Villari Effect).

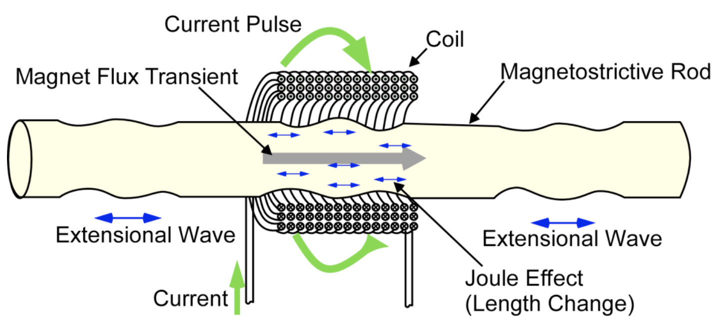

Figure 3. Generation of extensional waves in magnetostrictive rod by the Joule effect.

Generation of a torsional wave is conceptually similar to an extensional wave. In this case, the externally applied magnetic field is composed of one component aligned along the rod and another rotating around the rod. The superposition of these two components results in an applied magnetic field vector oriented generally along the rod, but with its tip precessing around the rod's circumference. Rapidly altering the directions of the applied fields results in a helically propagating torsional strain wave. This summed longitudinal and rotational magnetic field based generation of a torsional wave is referred to as the Wiedemann effect.[18] Figure 4 illustrates the Wiedemann effect: a torsional stress pulse is produced in a magnetostrictive rod when a current pulse is applied to a coil surrounding the rod, causing a magnetic flux transient to interact with an azimuthal magnetic field existing in the rod. Such an azimuthal magnetic bias may be established in the rod by passing a direct current (DC) through the rod. The vector sum of the axially changing flux and the azimuthal bias produces a helical field that twists the rod and initiates a shear stress pulse in the rod. This shear stress pulse propagates as a torsional wave at a speed less than that for the extensional wave. On its return to the coil, the torsional wave produces an output voltage across the coil by the inverse Wiedemann effect (Matteucci Effect) through Faraday's law.

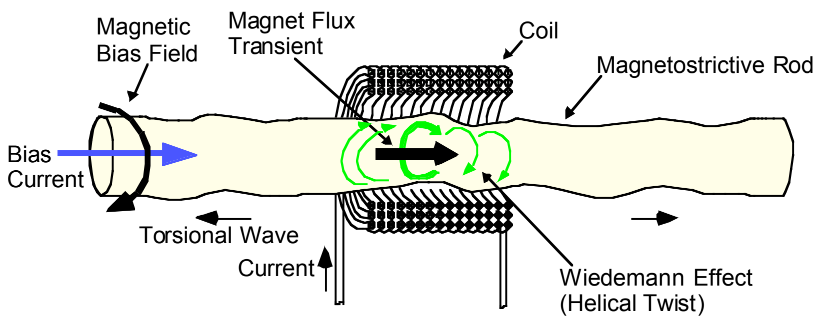

Figure 4. Generation of torsional waves in a magnetostrictive rod by the Wiedemann effect.

The amount of torsional wave delay depends upon the specific shape of the waveguide. Kim and Bau[15] have demonstrated using both closed form mathematical analysis and FEA that a diamond shaped cross section with a 3:1 aspect ratio produces about a 15 percent propagation delay as compared to the approximate 5 percent propagation delay of a square cross section element. The current project has elected to follow the Kim and Bau design initially, but will be attempting further optimization based on the more complex geometries (i.e., cusps interconnecting the diamond tips) that will increase the probe fluid inertia.

4.2.1.4 Initial Experimental Prototype

The objective for the first year experimental prototype was to construct and demonstrate a working extensional and torsional wave propagation and measurement assembly and to capture ultrasonic signals that correspond with a computational simulation of the experiment. This has now been accomplished. The present version of probe system consists of the blade and ultrasonic transducer as shown in Figure 5a. Figure 5b shows a schematic cross-section of the driver and receiver coils. For the initial prototype to minimize differences from known technology, project staff elected to follow the experimental set-up developed by Dress and Miller[8].

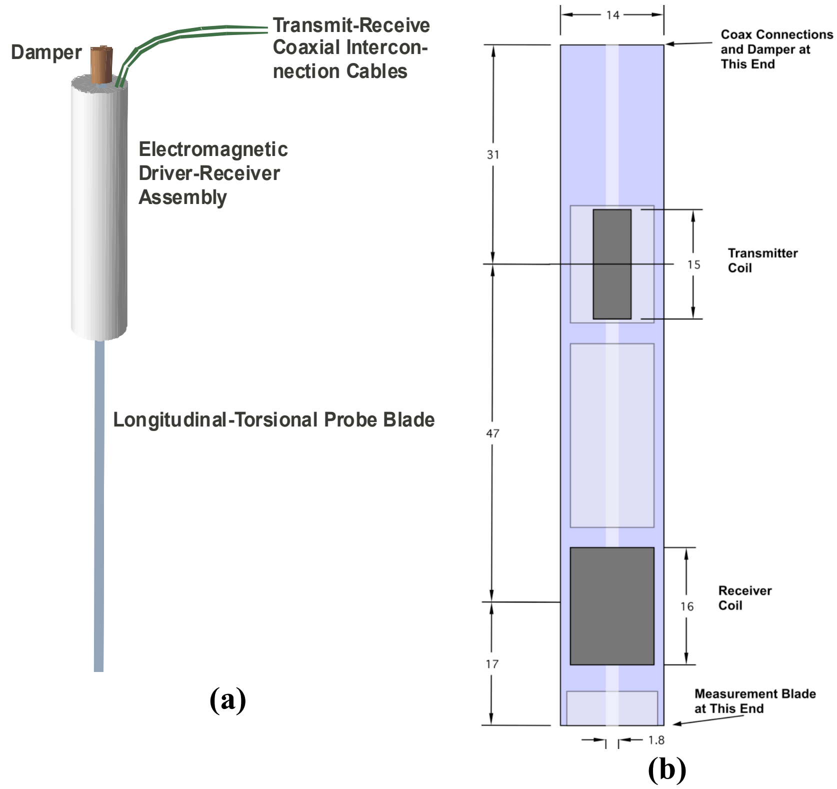

Figure 5. (a) Conceptual illustration of torsional ultrasonic probe and (b) Cross section of the driver-receiver assembly

Separate excitation of the extensional and torsional waves is useful to facilitate separation of torsional and extensional echoes. The circuit of Figure 6 illustrates the use of two separate coils, one each for drive and receive. To generate an extensional wave, a DC current is applied to the bias coil that is aligned with the drive and receive coils. In practice, a permanent magnet was typically employed as the biasing element. This bias moves the operating point on the magnetostrictive response curve (see Figure 7) to a point of maximum length change per unit of magnetization strength (i.e. maximizing the Joule Effect). A generation pulse is triggered in the driver coil, which creates an extensional wave by the Joule Effect. The return echoes are picked up by the receiver coil (Faraday Effect). Generation of the torsional wave requires applying a DC current through the magnetostrictive rod to establish an azimuthal magnetic field around the rod. After turning on the DC current, a generation pulse is triggered creating a torsional wave by the Wiedemann Effect. The return echoes are picked up by the receiver coil by the inverse Wiedemann Effect (Matteucci Effect).

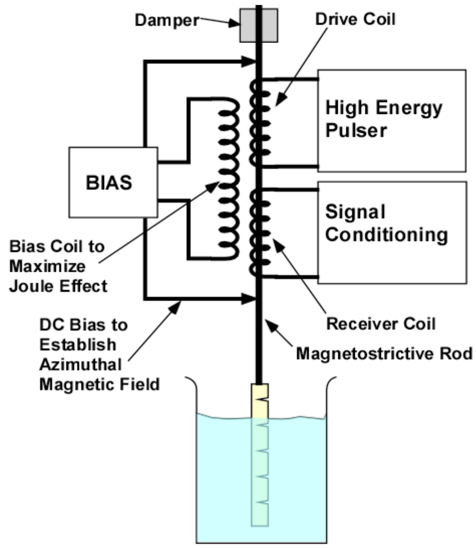

Figure 6. Bias, drive, and receive circuits for separate driver and receiver coils.

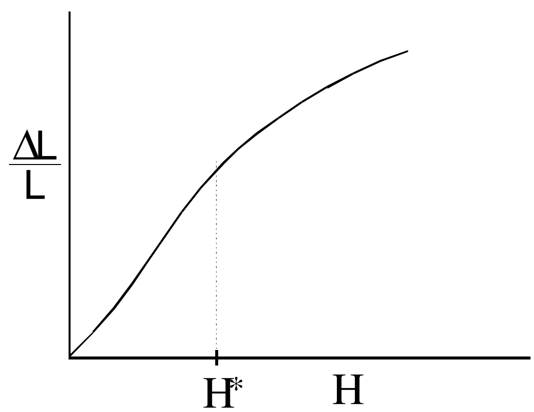

Figure 7. Magnetostrictive effect showing bias field H* about which the Joule Effect is maximized.

A benefit of separating driver and receiver coils is that the impedance of the coils (i.e. the number of winding turns) can be optimized. Drive coils can be made to operate at low voltage and high current by a small number of turns of large cross-section wire (about 64 turns in the present system). Receiver coils can be made sensitive by increasing the number of turns and decreasing the wire cross-section (about 5000 turns employed in the present system).

A Panametrics™ NDT model 5800 pulser/receiver was employed to drive and receive the electromagnetic pulses. The bias current was supplied using a DC power supply and the pulses were recorded using a digital oscilloscope. The experimental probe configuration and representative data are shown in Figure 8.

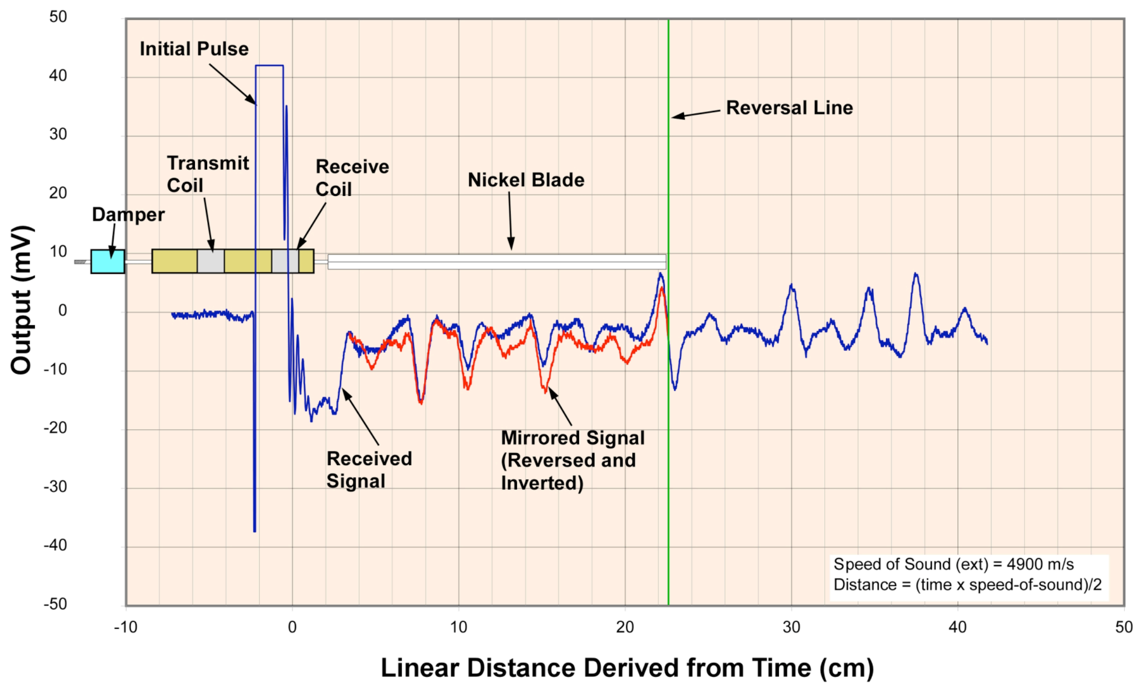

Figure 8. Nickel blade experimental signal (actual configuration vertical; rotated for ease of plotting)

In addition to assembling the initial ultrasonic probe system, project staff designed and fabricated an atmospheric pressure, low temperature, de-aerated water testing apparatus. The level measurement tank is a clear acrylic tube to allow visual comparison of the measurements with the tank condition. The tank system includes a vacuum pump-down capability and water heating system to remove dissolved air in the water.

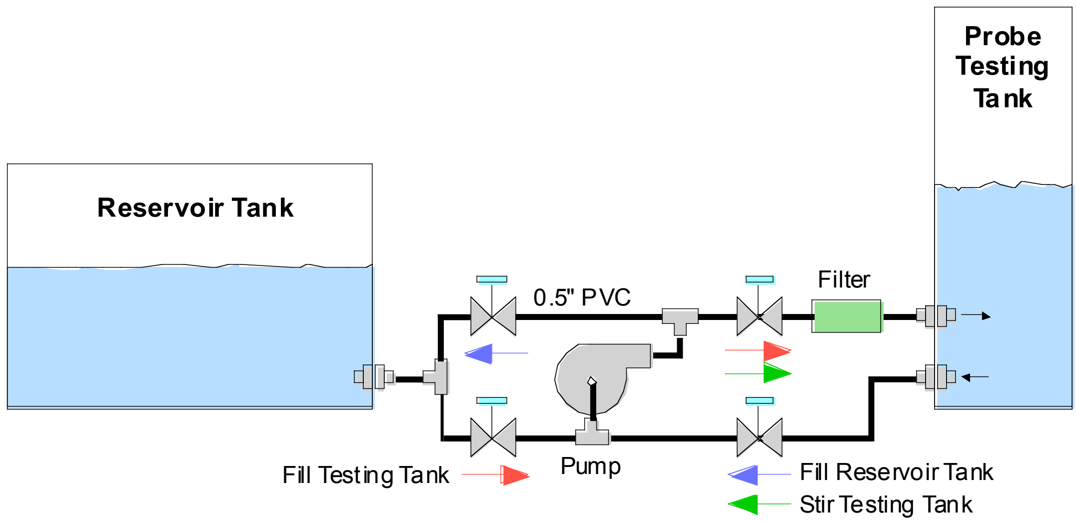

Figure 9. Water level testing apparatus

4.2.1.5 Computational Model Development

The objective of the computational modeling is to optimize the overall measurement system design. Probe properties such as transitions from the shaped blade section (diamond cusp) to a cylindrical probe can be more easily optimized computationally than experimentally. The overall ultrasonic waveguide modeling was finite element based and implemented using the ANSYS™ multi-physics software package. During FY2005 the computational modeling focused on setting up the initial probe blade and coolant model and then performing ultrasonic transmission simulations that could be experimentally benchmarked to verify the model validity.

While the current simulation is of significantly higher physical fidelity than has ever previously been reported for this type of system, a detailed three-dimensional model of the probe geometry and pulsed ultrasonic propagation along it remains beyond realistic computational limits. Ultrasonic waves interact with millimeter scale structures and the ultrasonic wave packets have frequency content of hundreds of kilohertz. Meshing the extended wave guide geometry on a sub millimeter scale while computing the finite element physics interaction on a few microsecond time scale as would be necessary for a full system simulation remains beyond the computational state-of-the-art. The project has, therefore, elected to individually analyze ultrasonic propagation through all of the component probe segments (basic segment, notch, mounting bracket, etc.) individually as opposed to as an entire assembly.

The waveguide distortion disturbs the fluid environment as the torsional and longitudinal waves travel down the length of the waveguide. The ANSYS multi-field solver provides a bi-directional fluid structure interaction (FSI) capability for time transient or steady state analysis with moving / deforming geometry. The interaction of the fluid and the structure at a mesh interface causes the acoustic pressure to exert a force applied to the structure and the structural motions produce an effective fluid load. In the first year, the blade has been modeled independently from the electromagnetic generation of the ultrasonic pulse.

A two dimensional finite element model has been produced and used to compare the propagation of extensional (longitudinal) waves with experimental measurements. The 2D model also serves as a demonstration of the multi-physics ability of ANSYS as the fluid and structural degrees of freedom are coupled together. A three-dimensional model for a single material continuous waveguide segment (see Figure 10) within a water sphere has also been produced.

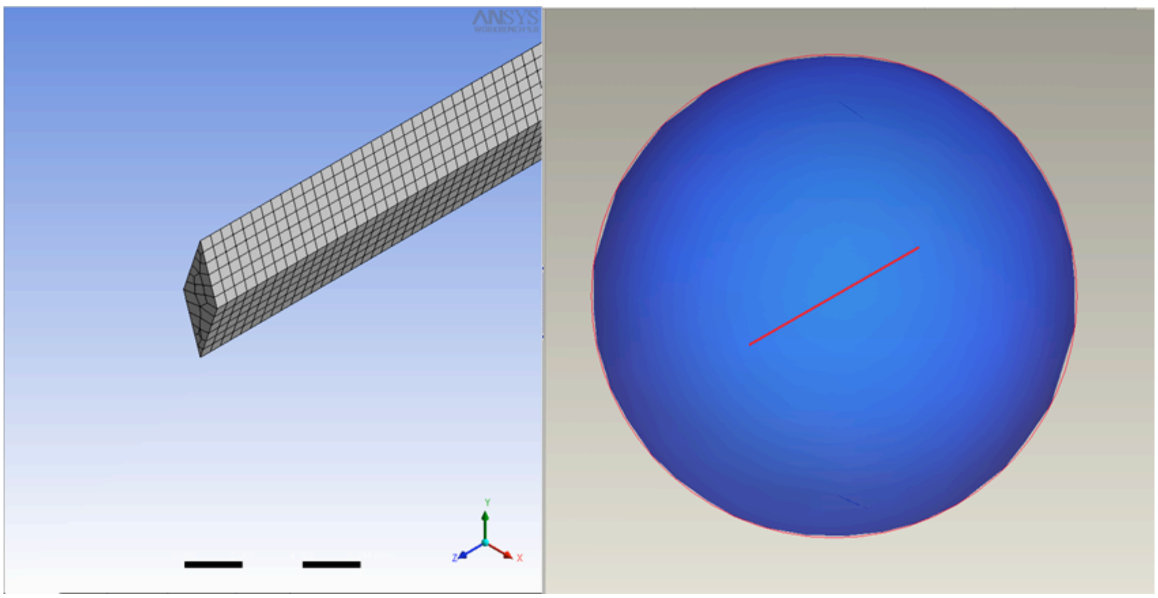

Figure 10. Preliminary 3D model of a diamond shaped probe, with aspect ratio of 3, enclosed in a fluid sphere.

4.2.1.6 Benchmarking Measurements

Both experimental and a computational simulation of extensional wave propagation was performed to validate the computational methodology. The first experimental probe consisted of a cylindrical piece of nickel alloy 61. The rod was 48.2 cm in length with the excitation occurring at 8.7 cm from one end of the rod and the receiver positioned at 13.6 cm relative to the same end. The ANSYS model was constructed with these same geometric dimensions and is shown in Figure 11. It is fixed on the proximal end and the 60 N force is applied for 5 μs.

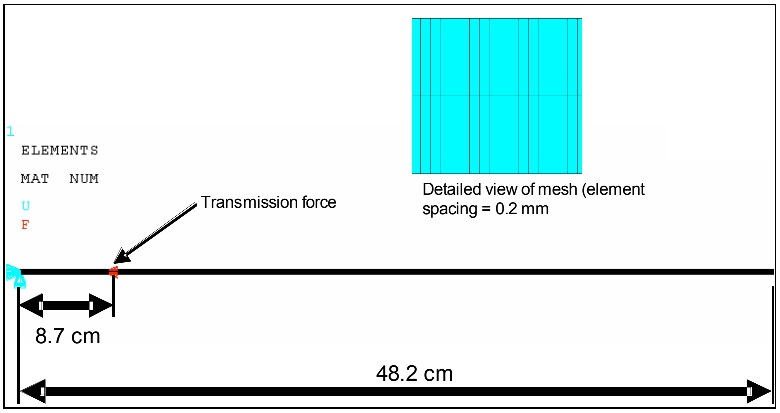

Figure 11. ANSYS geometry and mesh of nickel probe used in extensional wave propagation.

The receiver node deflection at 13.6 cm from the proximal end was plotted as a function of time along with the wave plot from the real rod. The ANSYS model output was normalized to match the measured signal. The computational time step size was 100 ns, which was derived by trial and error. Larger time steps decreases the resolution of the propagating wave and creates larger "ripples" that die out more slowly. Smaller time steps capture the wave better with the caveat that the minimum time step used must be greater than the speed of sound through an individual element. Thus, the minimum step size for a 200-micron element is 41.42 nanoseconds (speed of sound in Ni = 4828 m/s). The pulse length of the excitation was also iterated to emulate the pulse length (seen in the plots) exhibited on the real rod. Figure 12 shows the comparison of the ANSYS rod distortion to the experimental measurement.

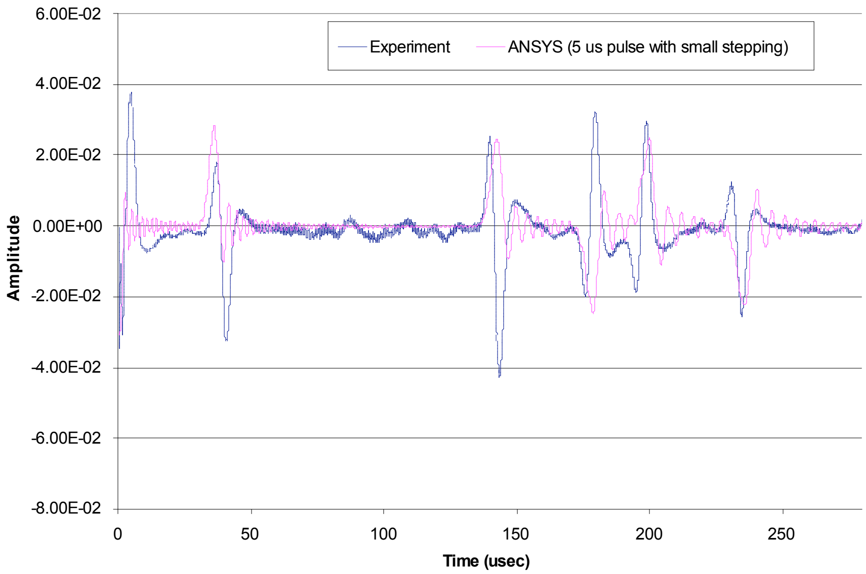

Figure 12. Comparison of the FEA solution to the experimental extensional wave propagation.

4.2.2. Cooled Fluid Based Level Sensor Development

Thermal Probe Level Sensors (TLPS) have previously been developed for in-vessel application at LWRs[19-23] as results of initiatives triggered by post TMI-2 recommendations. Most of them have been quite successful in tests and a few of them have been actually installed in large commercial reactors. TLPS are presently available as a commercial, non-nuclear grade level measurement product.[24] However, not all TMI-2 recommended actions were fully implemented. In vessel level measurement received less emphasis and such "non pressure difference level measuring devices" are believed by the authors to have been implemented in only a few operating reactors. In-vessel level measurement is an issue that may be revisited for the new generation of reactor concepts.

4.2.2.1 Background

In the context of the aforementioned safety recommendations, it deserves mention that a Siemens (KWU) probe [reference 19] was designed and tested from 1983 until April 1984. As the next step, four of these probes were installed, in the reactor pressure vessels - RPVs of Graffenheifeld and Phillippsburg, two in each RPV, respectively in May and October 1984. As reported by the same reference [19], the in service performance was quite satisfactory.

All the TPLS reported in the literature, as well as our project, have in common the key physical principle that they rely on the large difference between the heat transfer coefficient of the immersed (liquid) and non-immersed (vapor) regions to determine liquid level. To measure this effect, some heat flux has to be promoted between the fluid and the measuring device, spanning the vertical region of interest. Staring from these basic points many possible routes and variants are available to accomplish the same goal and the concepts differ quite a bit. Table 4 highlights these differences.

In addition to the rechniques previously summarized, there is another concept described in Wenran et al[25], but because of missing details and incomplete figures it could not be included in the table. It is named "heating shell thermocouple level detector" - HTLD and it was developed at the Institute of Nuclear Energy Technology in Beijing, China. It seems that the concept makes use of emf difference generated by pairs of heated and unheated (comparing) TCs. Each of these differences (ΔT_i in terms of temperature) is then compared with the average between itself and its upper neighbor, as a result a code is generated giving a positive or negative indication of the level position between them. An assembly with eight detectors (16 pairs of TCs), whose ends were combined in a 4/4 series –parallel fashion and heating coils were joined to reduce connections, was installed in the NHR-2000 reactor. The assembly is able to span a range of 2.8 m giving a discrete indication of level positioning for seven non-uniformly sized regions.

Table 4. Known Concepts and Implementations of Thermal Probe Level Sensors - TPLSs

Name and reference	Means to induce the heat flux	Direction of the flux	Primary measuring components	Composition of the sensor elements inside the probe	Additional components / information	Output of the sensor element	Aggregation of sensor elements	Type of output information	Connections	Notes
Siemens, 1	Coiled thermal resistance	outwards (probe-fluid)	Resistance thermometer - RT	One heated and one unheated coiled RTs	Two outside compensating RTs (Wheat. bridge)	Compensated voltage across inside RTs, then coded	1 probe = 3 sensor elements	Discrete = below, between & above sensor elements	4 wires per sensor element	a, b
BICOTH pin type, 2	Heater pin	Same as above	Cr & Al differential thermocouples - DTCs (emf)	Thimbles of different length each containing a DTC train (segments in series)	A four wire heater pin centered in the probe	Binary coded indicating the section (1 of 23) where the level is in	1 probe(gauge) = 5 sensor thimbles, covering 23 sections of the level range	Discrete but detailed	2 wires per thimble + 4 for the heater pin	c
BICOTH "flexible" type, 2	Heater wire	Same as above	Same as above	5 wire-type flexible thimbles each containing a DTC train + a heater wire (ss sheath encased)	A grooved support rod	Same as above	1 probe(gauge) = 5 flexible thimbles, covering 23 sections of the level range	Same as above	4 wires per thimble	c
BICOTH "flexible" type, 3 and 4	Heater wire	Same as above	Same as above	4 wire-type flexible thimbles each containing a DTC train + a heater wire (ss sheath encased)	A gauge tube(L= 8 m x Ø = 5,2 cm) opened at the top and bottom houses the thimbles	Same as above	1 probe(gauge) = 2x4 flexible thimbles, covering 23 sections of the level range	Same as above	4 wires per thimble	d
TRICOTH, 5	Ni-Cr heater wire	Same as above	Cr, Al & Cons. differential thermocouples - DTCs (emf)	2 heater wires + 3 sensing wires, 2 of them making up a DTC train + a common Al wire	Structural inconel sheath. DTC train of 8 junctions and uniform sections	Trinary coded indicating the section (1 of 7) where the level is in	Probe signals can be combined to cover a lengthier range with the same resolution	Same as above	5 wires per probe	e, f

sensor element = the first level of aggregation of measuring elements to produce a meaningful signal to the sensor
BICOTH (TRICOTH) = Binary (Trinary) coded thermocouple array with heater

a - Two sensor elements can be fitted at same elevation, inside the probe, for redundancy at critical positions
b - Deployed configuration covered the top plenum region from the RCL nozzle to the upper plate
c - Probes tested with a measuring range of 2,6 m and varying section length (20 x 100 mm + 3 x 200 mm)
d - Deployed at Dodewaard natural çirculation BWR for a 1,1 m level range
e - The use trinary code and 3 sensing wires helps to optimize the amount of information per external wire connections
f - Also in ref. 5, the design of a more advanced sensor TRICOTH-III, an optimized stand alone probe, is is announced. Coaxial heater, 6 DTCs + 1TC in a 3,4 mm Ø outer sheath

As it is shown in Table 4, all TPLSs give discrete level position indications. Reference [23], however, mentions the development of new TRICOTH variant, in which, for the region where the level indication is in, they are planning to use a combination of the DTCs profiles that yield the region determination to recover a continuous level indication in that region. No details were given on how this is to be accomplished.

4.2.2.2 The TPLS concept being investigated

The key physical principle is the same, but a cooling fluid is used as the means to induce the heat flux whose direction is then inwards, from the measuring fluid to the probe. Two possibilities are being considered to promote the flow of the cooling fluid: natural circulation by cooling this fluid in a heat dissipater on the top of the probe outside the vessel and forced convection by exploiting pressure differences inside the vessel. Different association of thermocouples along the length of the probe are being considered, based on the experience reported in the literature, but also the inlet and outlet temperatures of the cooling fluid are going to be measured. The DTC and TC signals are going to be processed by a neural network (one-dimensional self organized map or back propagation algorithm) to produce a continuous level indication for the active probe length.

4.2.2.3 Project progress

The project comprises five phases: (a) Initial literature research; (b) Testing facility design and implementation; (c) Modeling; (d) Probe design and fabrication; and (e) Experimental tests, analysis and feedback.

Phase (a) has been completed and it was briefly reported in the previous background section and phase (b) is about 90% completed and it is described in the next section. In addition, numerical simulations have being done to check for viability of getting adequate flow rates of the cooling fluid in order to get good discrimination of the interface. The results were favorable and they are being used to start one of the probe designs.

4.2.2.4 Testing facility design and implementation

As it is shown in Figure 13, a low pressure (< 5 bar) and low temperature (<150°C) facility for testing the probes was designed and constructed at IPEN. It can test probes up to 4.5m of active length and provides two equally instrumented and interconnected test regions for such. These test regions are made up of two vertical pipes of 5 m length with heaters in their lower end.

Simultaneous static and dynamic tests can be run with even or uneven level configurations. The facility was conceived to be easily operated, but because of limited in-house experience, it is expected that some minor adaptations and improvements will be made during the startup.

Among the few minor things that remain to be concluded one should note that a small water demineralizer has yet to be included and the facility sensors have to be calibrated; that should be done two months before starting the tests.

To give an idea of the actual facility, three pictures of its past and present status are included in Figure 14, Figure 15, and Figure 16.

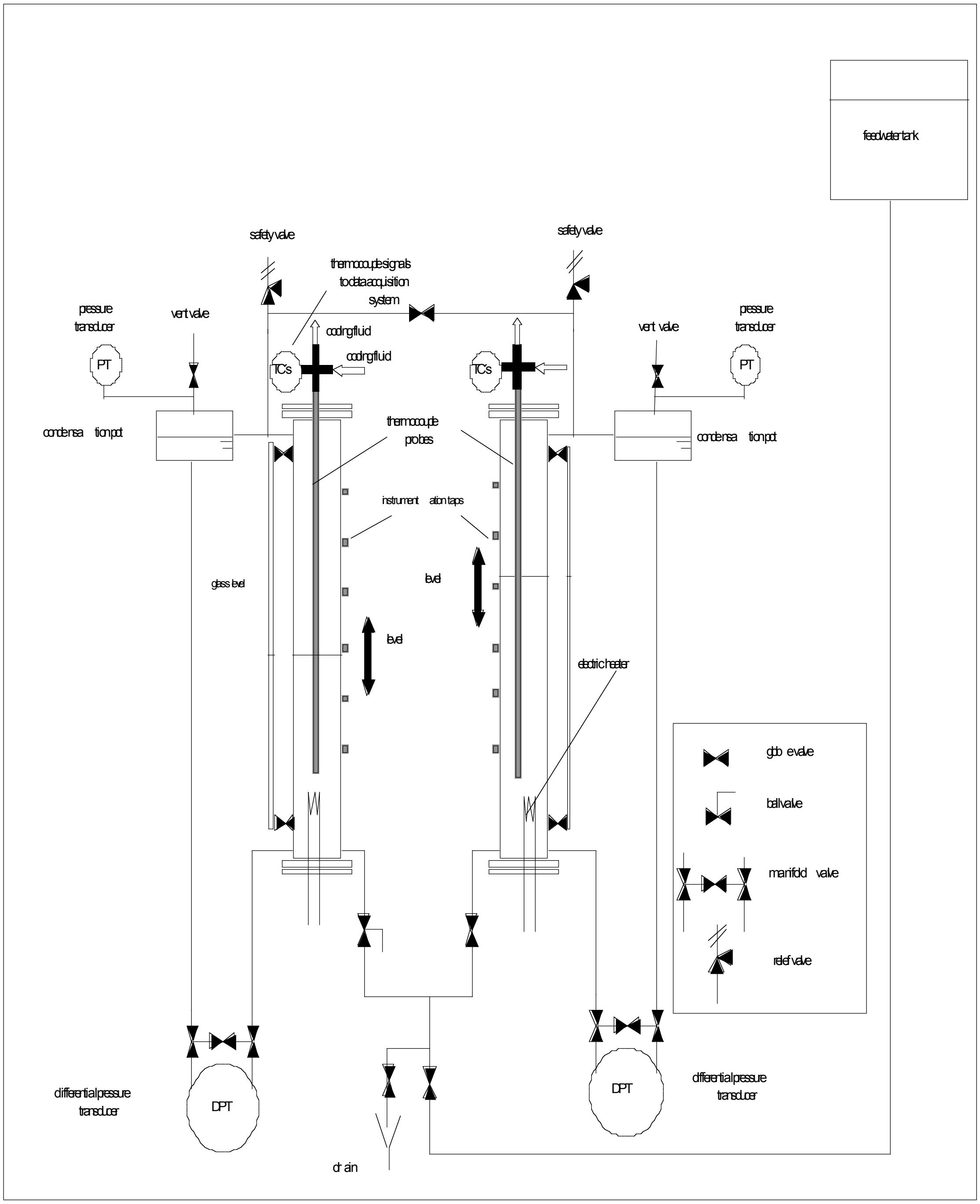

Figure 13. Schematic of the Test Facility

The lower part of the test facility is shown in Figure 14, where one can see, for each of the insulated vertical pipes (test regions), the respective line coming down from the condensate pot and the bottom connections to the pressure transmitter.

Figure 15 shows the upper part of the test regions with their respective condensation pots and safety valves. It should be noted that neither the discharge line of the safety valves was connected nor the insulation of the pipes were assembled at the time this photo was taken.

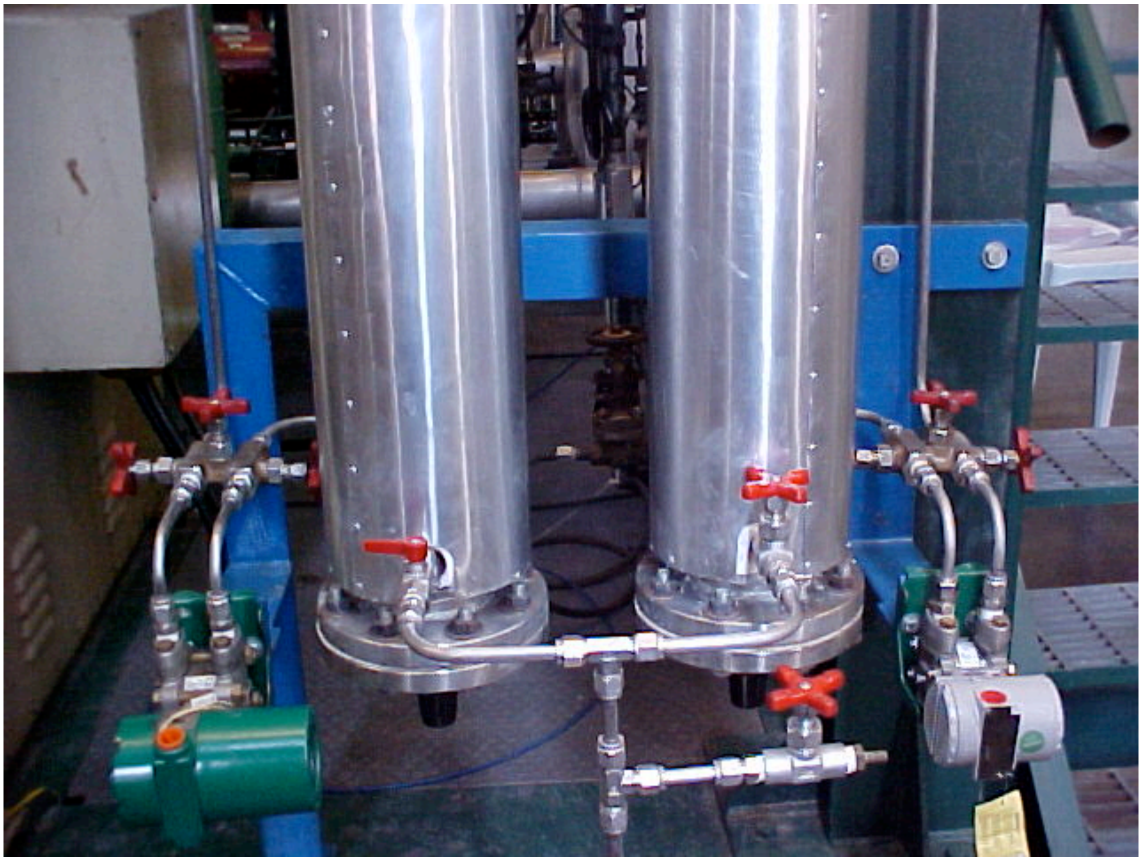

Figure 14. Lower Part of the Test facility

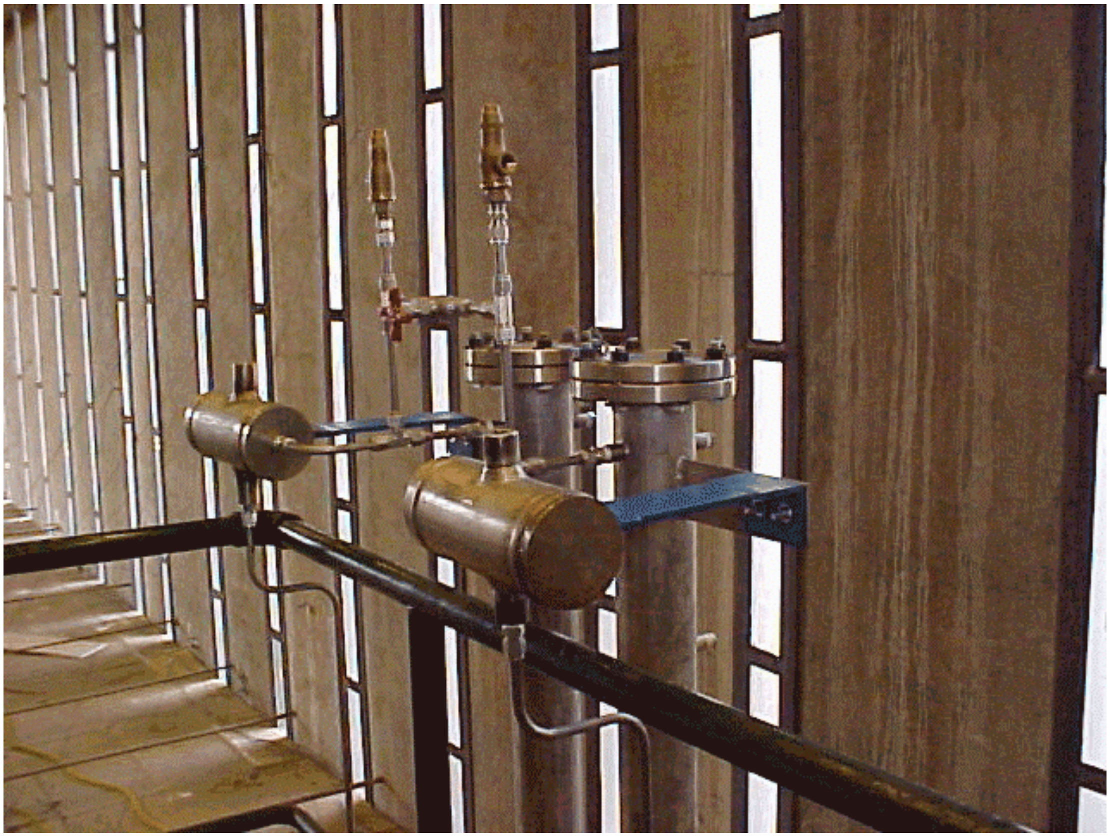

Figure 15. Upper Part of the Test facility

Finally Figure 16 shows a view of test region where one can see the additional instrumentation taps and glass level viewers.

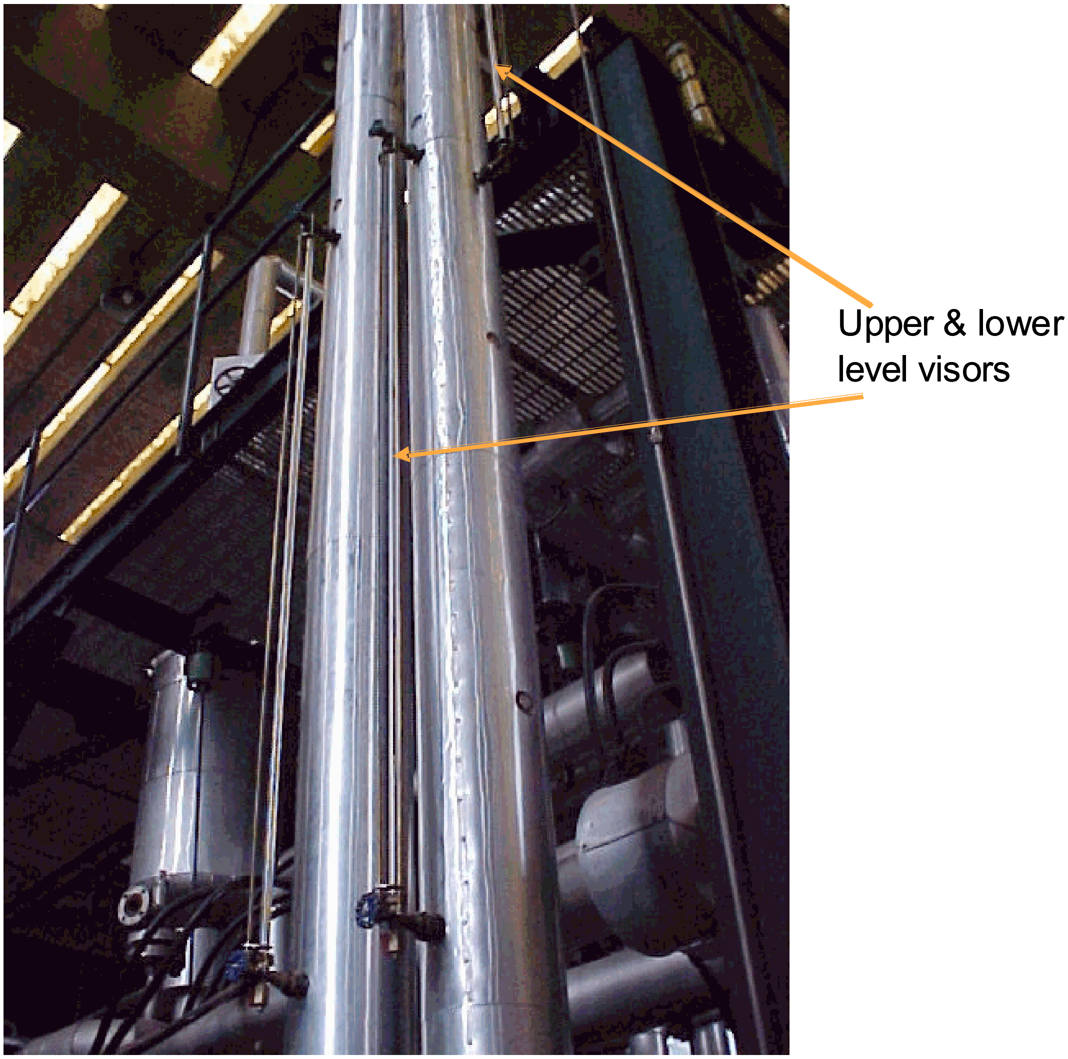

Figure 16. Partial Frontal View

4.3. Reactor Transient Analysis

The Reactor Transient Identification and Classification System (TIS) has as primary goal to improve human reliability and, thus proactively, to increase reactor operational safety, thereby improving plant availability and profitability. This goal will be achieved by rapidly identifying and classifying transient events on-line and in this way providing support to reactor operator actions and decision making.

The concept of the Transient and Classification System in development, proposed by Baptista and Barroso[26], is based on the use of artificial neural network (ANN) specifically of self-organizing maps (SOM).[27] Up to this point the results obtained[26,28] have confirmed that SOM are a quite promising tool in the identification of initiating transients and their capability of identifying and classifying IRIS operational condition has already been demonstrated.

The scheme shown in Figure 17 has been used in TIS development and the following steps of this process have been accomplished:

- Software developed for square and triangular grids testing;
- Sensitivity analyses for grid size;
- Sensitivity analyses for grid array;
- Sensitivity analyses for buffer size;
- Sensitivity analyses for SOM parameters;
- Sensitivity analyses for transients classes

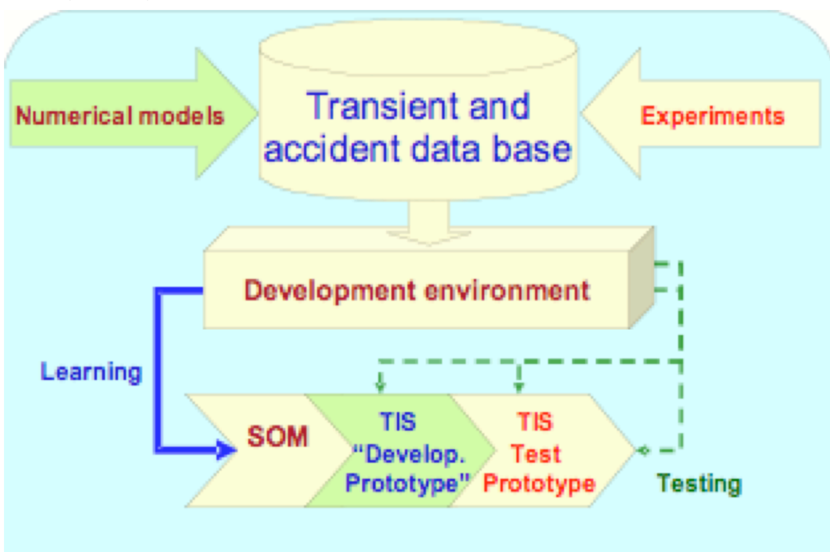

Figure 17. Transient Identification System

TIS will evaluate reactor operational status through monitoring a few process sensor signals. Two different approaches have already been tested, one using the evolution of 9 parameters [26] and another using 8 parameters [28] all of them obtained from 10 reactor measurements channels: 2 power channels (reactor and steam generator), 6 temperatures (core outlet), upper plenum (riser), inlet and outlet of steam generator primary side, downcomer, pressurizer), 1 pressure (in primary system) and 1 water level (in pressurizer). The investigation of other parameters is also considered in project development.

Figure 17 shows that the parameters required for the model development can be obtained from numerical models and experiments, when available, covering a range of reactor conditions. The normal operation, transient and accident data used until now were obtained mainly using a simple model[29] that provides fast results. Next step of TIS development, aiming at a version closer to IRIS performance, requires data from normal operation, transient and accident simulations that are generated with more sophisticated models like MODELICA and RELAP.

CNEN has been using RELAP model of IRIS reactor developed by University of Zagreb and Westinghouse for steady state calculations and power transients changes in steps and ramps.[30] While steady state results are consistent with expected values, those from power change transients presented some problems in its evolution and therefore minor changes were introduced in control part of this model in order to overcome this difficulty. Figure 18 shows the evolution during 2000s of the pressure in primary system during a step power change from 100% to 90%, using the original model (blue line) and the changed one (red line).

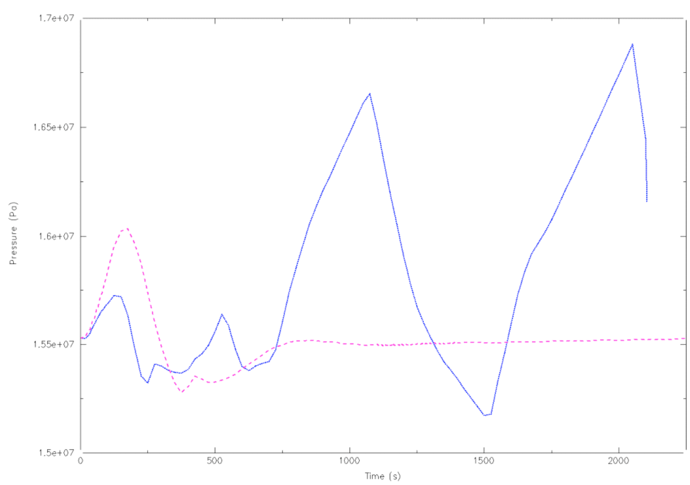

Figure 18. RELAP Results

RELAP runs are time consuming and thus its results, although very detailed and accurate, can not be the main analytic tool used as a source of normal operation and transient data but it will be used mainly for checking results and for getting accident data that can not be provided by other tools. The main tool foreseen to provide data of normal operation and transient conditions is MODELICA, the plant simulator developed by Westinghouse in co-operation with POLIMI, Italy. MODELICA includes control systems for IRIS and can simulate the plant dynamic response very quickly being, therefore, the proper tool for providing reliable data for TIS development. Table 1 presents simulations that have already been used in TIS development [26, 28] and that shall be, in the near future, carried out with MODELICA in order to supply information for the next phase of TIS development.

Table 5. Simulations to be carried out using MODELICA

Steady States (Power %)	Normal Transients		Abnormal transients
	Ramp Power change (Initial Power% ➔ Change rate)	Step Power change (Initial Power% ➔ Change step)	
20%	25% ➔ +5%/min	100%□ ➔ –10%	100% ➔ Step – 70%
25%	30% ➔ +5%/min	90% □ ➔ –10%	Safety Valve Opening
30%	40% ➔ +5%/min	80% ➔–10%	100% Small LOCA
35%	50% ➔ +5%/min	70% ➔–10%	100% SCRAM
40%	60% ➔ +5%/min	60% ➔–10%	60% ➔ Step +50%
45%	70% ➔ +5%/min	50% ➔–10%	100% Turbine trip
50%	80% ➔ +5%/min	40% ➔–10%	
55%	90% ➔ +5%/min	30% ➔–10%	
60%	100% ➔ –5%/min	20% ➔ +10%	
65%	90% ➔ –5%/min	30% ➔ +10%	
70%	80% ➔ –5%/min	40% ➔ +10%	
75%	70% ➔ –5%/min	50% ➔ Step +10%	
80%	60% ➔ –5%/min	60% ➔ Step +10%	
85%	50% ➔ –5%/min	70% ➔ Step +10%	
90%	40% ➔ –5%/min	80% ➔ Step +10%	
95%	30% ➔ –5%/min	90% ➔ Step +10%	
100%			
105%			
110%			

Several different aspects of TIS have already been implemented and tested. Concerning the input data for TIS the main items that have already been investigated are: number of reactor operational parameters in the input, size of the buffer, frequency of the parameters sampling, normalization of the input data, normalization of buffer data, and influence of different parameters normalization. Related to SOM engine the main studied points were: grid size, cell form (squared and triangular), classification based on Euclidian distance or frequency of cell activation. Regarding the arrangement of the results in the output grid the more important options considered were: simple classification by SOM, use of Learning Vector Quantization and different weight initialization. The time performance of the training phase of TIS was also investigated using grids from 5X5 to 25X25.

Results from most of this investigation have been presented and discussed in technical and scientific meetings [26, 28, 29, 30]. Figure 19 presents a result obtained after changing the initial weights to improve classes' aggregation. At left the output grid with lines representing transient evolution shows good identification of tested transients and the right side illustrates the aggregation of normal operation in a contiguous zone surrounded by the abnormal zone.

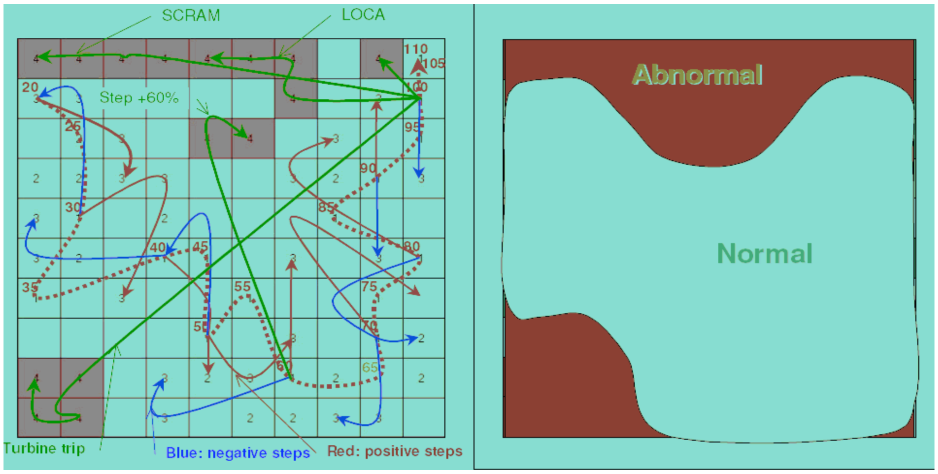

Figure 19. Results from Transients Identification

Future Activities
Many activities have already been accomplished providing results and conclusions however many other developments are still required till project completion. The next steps of TIS development include:

- More detailed and in-depth investigations of some aspects
  - New analyses with grid sizes up to 25 x 25 cells or more
  - Detailed studies on the number and type of input variables
  - Algorithm to convert the irregular topological map into a regular display screen
- Repeating some tasks using more accurate input data
  - Use of plant model with RELAP for accident sequences
  - Use of MODELICA data for normal steady state and transient conditions
- Investigation of new issues
  - Studying the use of the "Mexican hat" –type neighborhood function
- New developments
  - Coupling of TIS model with plant model and testing
  - Design of a new man-machine interface
  - Conclusion of the development prototype.

4.4. Supervisory Control Strategy Development

This task is beginning in FY2006

4.5. Operator Interaction With Control and Protection Systems

This task is beginning in FY2006

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